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Reduced-Chromium Stainless Steel Substitutes Containing Silicon and Aluminum

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	mg	milligram
atm	atmosphere	mg/cm ²	milligram per square centimeter
°C	degree Celsius	min	minute
cm	centimeter	mm	millimeter
ft ³ /h	cubic foot per hour	MPa	megapascal
g	gram	pct	percent
h	hour	psi	pound per square inch
in	inch	V	volt
in/in·min ⁻¹	inch per inch per minute	vol pct	volume percent
in/min	inch per minute		

REDUCED-CHROMIUM STAINLESS STEEL SUBSTITUTES CONTAINING SILICON AND ALUMINUM

By M. L. Glenn¹ and D. E. Larson¹

ABSTRACT

The Bureau of Mines is conducting research on Fe-based alloys using Si and Al additions to reduce the Cr required for heat-resisting applications. Part of this research is being done to evaluate alloys containing (8-10)Cr-(10-14)Ni-(0-8.5)Si-(0-4)Al to determine which of these alloys have austenitic structures, as well as fabrication properties and oxidation resistance sufficient to substitute for type 304 stainless steel.

Based on initial results, an Fe-10Cr-11Ni-5Si alloy and an Fe-8Cr-13Ni-5Si alloy were selected for evaluation of oxidation, stress rupture, and tensile properties. Both alloys have oxidation resistance at 700° and 800° C that is better than that of type 304 stainless steel. The stress rupture strengths are less than that of type 304 stainless steel but significantly better than that of commercial heat-resisting steels with similar Cr contents. Yield strengths of the alloys were equivalent to that of type 304. Both alloys had high tensile strengths comparable to those of stainless steels that transform to martensite during straining (e.g., type 301). These alloys have weld-hot-cracking resistance comparable to that of type 304 stainless steel. This initial study shows that Si has potential as a substitute for Cr in stainless steels for heat-resisting applications.

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INTRODUCTION

Approximately 70 pct of the Nation's supply of metallurgical Cr is used in the production of stainless steels, which usually contain from 12 to 28 pct Cr. Stainless steels are primarily used for applications that require either ambient-temperature corrosion resistance or high-temperature (600° to 800° C) oxidation and stress rupture resistance. The Bureau of Mines is conducting research on substitutes for both of these applications. This report concentrates on the conservation of Cr in stainless steels used for heat-resisting applications.

Lowering the Cr content of stainless steels has been the objective of several investigations. International Nickel Co. (INCO) conducted research on a stainless steel containing 12Cr-12Ni-(1-3)Si-(1-3)Al, primarily for use in automotive exhaust systems. This alloy is oxidation resistant and possesses good high-temperature stress rupture properties (1).² Under a recent Bureau of Mines research contract, Floreen of INCO investigated a 10Cr-24Ni-2Al-3Si alloy having oxidation resistance at 900° C and stress rupture resistance nearly equivalent to that of type 304 stainless steel (2-3). Research

by Stephens of NASA also showed the potential for reduced-Cr substitutes for type 304 stainless steel. Stephens' 12-pct-Cr alloys with either Si or Al additions had oxidation resistance equivalent to that of type 304 stainless steel (4-6).

The goal of this research was to study the feasibility of reducing the Cr content of stainless steels used for heat-resisting applications by replacing part of the Cr with Si and/or Al additions. The research was conducted in two stages. First, iron-based alloys containing 8 to 10 pct Cr were screened for compositions that were austenitic, could be fabricated without cracking, and had good resistance to oxidation. During the second stage of the research, two alloys were selected for evaluation of room- and high-temperature mechanical properties and long-term resistance to high-temperature oxidation. In this research, the properties of the alloys were compared to those of type 304 austenitic stainless steel (18Cr-9Ni) and to those of type 410 stainless steel (12Cr), which is representative of low-Cr heat-resisting alloys.

ALLOY SELECTION

SELECTION OF COMPOSITION

The room-temperature structure of Cr-Ni stainless steels can be made either austenitic, ferritic, or martensitic by making small changes in the composition. Close control of the alloy composition was necessary to insure the desired austenitic structure. The Schaeffler diagram (7, pp. 2-3) was used to initially predict alloy structure from the composition. The Schaeffler diagram is a plot of structure as a function of Cr-equivalent elements (ferrite formers) and

Ni-equivalent elements (austenite formers) as defined by the following equations:

$$\text{Cr equivalent} = \text{pct Cr} + 2(\text{pct Si})$$

$$+ 1.5(\text{pct Mo}) + 5(\text{pct V})$$

$$+ 5.5(\text{pct Al}) + 1.75(\text{pct Cb})$$

$$+ 1.75(\text{pct Ti}) + 0.75(\text{pct W});$$

$$\text{Ni equivalent} = \text{pct Ni} + \text{pct Co}$$

$$+ 30(\text{pct C}) + 25(\text{pct N})$$

$$+ 0.5(\text{pct Mn}) + 0.3(\text{pct Cu}).$$

²Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

The composition of type 304 stainless steel has been optimized at a Cr equivalent of about 18 pct and an Ni equivalent of about 12 pct. Lower Cr contents can theoretically be compensated for by additions of other Cr-equivalent elements such as Si or Al. However, the Schaeffler relationships were found to be inaccurate for 8-10Cr alloys, so additional Ni-equivalent elements were needed to retain the austenitic structure. The approach of the research was to add sufficient Si and/or Al for oxidation resistance and to add Ni to stabilize the austenitic structure. Approximately 40 alloy compositions containing 8 and 10 pct Cr and various Si, Al, and Ni contents were selected for initial evaluation.

SELECTION PROCEDURE

One-hundred-gram alloy charges were prepared from electrolytic grades of Fe, Mn, and Cr and high-purity grades of Al and Si. Carbon (0.05 pct) was added in the form of an Fe-2C master alloy. The alloys were dc arc-melted five times in a furnace chamber that was evacuated and backfilled with 1 atm helium. The composition of 11 alloys selected for chemical analysis (table 1) showed close correlation between nominal and analyzed compositions. Nominal compositions are used throughout the report.

After melting, the alloys were homogenized for 20 h at 1,200° C in a vacuum

furnace at 10^{-4} Torr. The alloys were hot-rolled at 1,100° C in three passes from an initial thickness of approximately 1/4 in to a final thickness of approximately 1/10 in. The alloys were visually assessed during the hot rolling for edge cracking and other indications of poor workability.

The structure of the alloys, in particular the amount of ferrite or martensite contained in the austenitic matrix at room temperature, was measured with a Magne-Gage.³ This instrument measures the force required to pull a standard magnet from a sample surface containing ferrite or martensite (both magnetic) and austenite (nonmagnetic). The Magne-Gage reading is converted to a ferrite number which is an approximation of the percent ferrite or martensite. The Magne-Gage was used and calibrated in accordance with the American Welding Society standard procedure (8).

To evaluate the resistance of these alloys to oxidation, weight gain oxidation evaluations were conducted in accordance with ASTM procedure G54-77. Specimens approximately 3/4 by 1-1/4 by 1/8 in were cut, polished (120 grit), cleaned, and weighed prior to exposure. The specimens were placed in a 750° C furnace, cooled, and weighed after

³Reference to specific products does not imply endorsement by the Bureau of Mines.

TABLE 1. - Composition of alloys, percent¹

Alloy	Nominal composition				Chemical analysis				
	Cr	Ni	Si	Al	Cr	Ni	Mn	Al	Si
3.....	10	10	4	0	9.26	10.0	0.73	<0.05	4.36
4.....	10	10	4.5	0	9.75	10.0	.87	<.05	4.69
5.....	10	10	5.5	0	9.89	10.1	.87	<.05	5.80
21.....	10	12	2.5	2.5	10.2	12.6	.95	2.52	2.82
24.....	10	12	2	2	9.51	12.5	.86	1.99	2.15
25.....	10	12	1.5	1.5	9.84	13.0	.90	1.54	1.67
35.....	10	14	0	2	9.81	14.7	.78	1.94	.12
38.....	8	10	4	0	7.38	10.5	.90	<.05	4.24
39.....	8	10	5	0	7.98	10.4	.78	<.05	5.28
40.....	8	10	6	0	7.90	10.4	.86	<.05	6.26
41.....	8	12	5	0	7.78	11.5	.84	<.05	5.17

¹All alloys contain 1 pct Mn and 0.05 pct C, balance Fe.

150- and 400-h exposures. The weight gain of the specimens was compared to that of type 304 and 410 stainless steels, which were included in the test.

ALLOY SELECTION RESULTS AND DISCUSSION

Workability was judged based upon the number of cracks and depth of cracks observed after hot rolling. The results of the workability studies of the 8-10Cr alloys are tabulated in the appendix and summarized in figure 1. Slight changes in composition caused significant changes in workability. In general, the 10Cr-10Ni alloys containing 2.5 to 8.5 pct Si had the best hot-working properties, and the alloys containing Al had the worst hot-working properties. Three of the 8Cr alloys had good workability, and one had fair workability.

The Magne-Gage approximations of the structure (appendix) showed poor correlation between predictions from the Schaeffler diagram, originally developed for high-Cr-content alloys, and actual existing phases in the 10-pct-Cr alloys. The approximations were, therefore, plotted for three Ni levels (one each at 10, 12, and 14 pct Ni) through the Fe-10Cr-Ni-Al-Si phase diagram (fig. 2). For 10 pct Ni, a small austenitic (nonmagnetic) region was found, encompassing 4- to 6-pct-Si alloys. A larger austenitic region was found at 12 pct Ni. All the compositions with 14 pct Ni were austenitic. Overall, the data indicated that at least 14 pct Ni is needed for austenitic alloys containing Al without Si, but Ni contents as low as 10 pct can be used for austenitic alloys containing only Si.

Sixteen 10-pct-Cr alloys having various additions of Si and/or Al were selected for oxidation evaluation. The oxidation rates at 750° C for these selected alloys are summarized in table 2. All but one of the alloys evaluated with Si additions or combined Si-Al additions had oxidation resistance equal to or better than that for type 410 or 304 stainless steels. However, alloys with only Al additions scaled severely and spalled unless the Al content was 4 pct or greater.

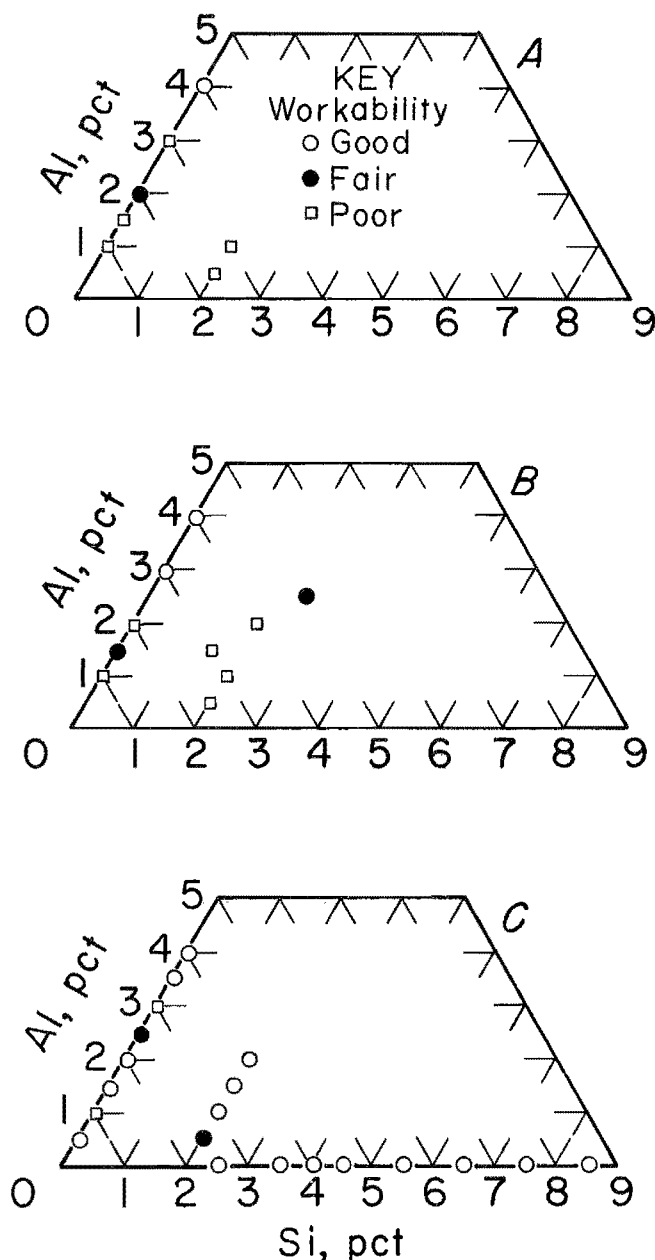


FIGURE 1. - Relative workability of alloys. All alloys contain 1 pct Mn and 0.05 pct C. A, 14 pct Ni; B, 12 pct Ni; C, 10 pct Ni.

To evaluate the potential of reduced-Cr alloys, four 8-pct-Cr alloys that had various Ni and Si additions were also produced. Magne-Gage data (appendix) showed that additions of 12 pct Ni were required for an austenitic structure in the 5-pct-Si alloy.

ALLOY EVALUATION

The results of the alloy selection stage indicate a potential for reduced-Cr substitutes containing Si and/or Al for heat-resisting applications. To more

fully evaluate their potential as substitutes, two new alloys were selected for more extensive evaluation in the second stage of the research. This research concentrated on alloys with Si and without Al additions because such alloys were shown by the initial research to have the best workability. The first alloy, Fe-10Cr-11Ni-5Si (10Cr alloy), was selected because of its austenitic structure, oxidation resistance, and hot-working properties. A second alloy, Fe-8Cr-13Ni-5Si (8Cr alloy), was selected to evaluate the potential of using lower-Cr-content substitutes. In both alloys, the data from the alloy selection experiments were used to select the Ni contents that would develop an austenitic structure. During this second stage of this research, both

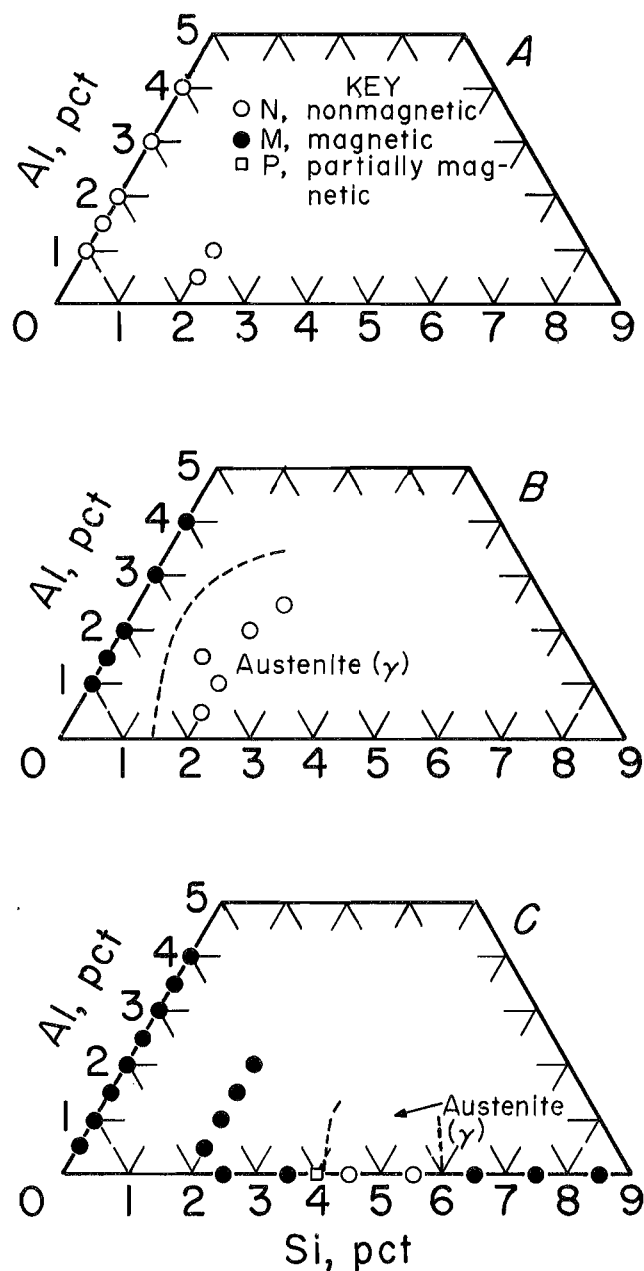


FIGURE 2. - Structure of alloys as affected by composition. All alloys contain 1 pct Mn and 0.05 pct C. Nonmagnetic, ≤ 10 ferrite number; partially magnetic, 10-20 ferrite number; magnetic, ≥ 20 ferrite number. A, 14 pct Ni; B, 12 pct Ni; C, 10 pct Ni.

TABLE 2. - Results of oxidation evaluation

Nominal composition, pct ¹				Weight gain after 750° C oxidation, mg/cm ²	
Cr	Ni	Si	Al	150-h exposure	400-h exposure
10	10	2.5	0	0.1	0.2
10	10	3.5	0	.1	.1
10	10	4.0	0	.1	.2
10	10	4.5	0	.1	.2
10	10	5.5	0	.0	.2
10	10	6.5	0	.2	.3
10	12	1.5	1.5	.1	.1
10	12	2	2	.0	.1
10	12	2.5	2.5	.1	.2
10	12	2	1	.1	.2
10	12	2	.5	.2	.2
10	14	0	1	(²)	(²)
10	14	0	1.5	(²)	(²)
10	14	0	2	(²)	(²)
10	14	0	3	(²)	(²)
10	14	0	4	.1	.1
8	10	0	5	.0	.1
18 ³	9	0	0	.1	.2
12 ⁴	0	0	0	.1	.2

¹All samples contained 1 pct Mn, 0.05 pct C, balance Fe.

²Spalled.

³Type 304 stainless steel.

⁴Type 410 stainless steel.

of these alloys were evaluated to determine mechanical properties, stress rupture resistance, oxidation resistance, and weld-hot-cracking susceptibility.

PROCEDURE

Fifty-pound ingots of these two alloys were vacuum-induction-melted from the same high-purity materials used in the alloy selection. The alloy ingots were step-forged at 1,100° C from an initial thickness of 1-3/4 in to 1 in with 1/4-in increments. Further reduction was done by longitudinal rolling at 1,100° C with 20-pct reductions until the final thickness was reached. The final thickness was 1/2 in for materials designated for mechanical property evaluation and 1/8 in for materials designated for weldability and oxidation evaluation.

Mechanical property evaluation of the alloys was in accordance with standard ASTM tests on specimens oriented with axes parallel to the rolling direction for comparative purposes. Tensile tests were conducted at a 0.05-in/in·min⁻¹ strain rate in a Baldwin Universal Testing Machine in accordance with ASTM E8-81. The round threaded tensile specimens used were 1/4 in diam by 1-in gage length. The hot tensile properties at 600°, 700°, and 800° C in air were evaluated in accordance with ASTM E151-64, which stipulates using self-resistance heating of the specimens. Round button-head specimens 1/4 in diam by 3-in gage length were used. Stress rupture tests at 600°, 700°, and 800° C were conducted on round specimens (1/4-in-diam cross section by 1-in gage length) in accordance with ASTM E139-79.

The oxidation of the alloys at 700° and 800° C was evaluated using a static weight-gain technique in accordance with ASTM G54-77. Specimens approximately 1 by 1-1/2 by 1/8 in were cut and polished to a 120-grit finish from both alloys and types 410 and 304 stainless steels for comparison. The specimens were then measured to determine the surface area,

cleaned in acetone and then ethanol, and weighed to the nearest 0.1 mg. Specimens of each alloy were placed on racks in hot furnaces for 1,000-h exposures. Oxidation was monitored during the exposure by removing and weighing the specimens at specific intervals. The test was terminated early if the oxide spalled. The weight gain per unit surface area was calculated and plotted as a function of time to provide a measure of the oxidation rate.

Austenitic stainless steels, particularly those containing Si, are usually susceptible to hot cracking during welding (9-10). Therefore, the weldability of these two alloys was evaluated by a Varestraint test for hot-cracking susceptibility.⁴ The Varestraint test simulates weld hot cracking in materials by the application of a strain to a specimen during welding. This test uses an apparatus that bends a specimen over a mandril (to provide a given strain) during welding. The strained weld surfaces are examined for hot cracks. Tests are conducted at several strain levels to determine the threshold strain, the strain at which the alloy just begins to develop hot cracks. The threshold strain is indicative of an alloy's susceptibility to weld hot cracking. The Varestraint test is fully described in a monograph on the subject (11).

To determine the susceptibility of the alloy composition to hot cracking, specimens of both alloys and one heat of type 304 stainless steel for comparison were submitted to the University of Tennessee for hot cracking evaluation. A moving-torch Varestraint device was used to evaluate 6- by 7/8- by 1/8-in specimens. The specimens were tested at augmented strains from 1 to 6 pct without using weld filler metal. The weld conditions were adjusted for each alloy to maintain a constant fusion zone width.

⁴Varestraint results courtesy of Dr. Carl Lundin, University of Tennessee.

RESULTS

Alloy Characterization

The alloys were checked for composition and metallographic structure prior to testing. The chemical analysis of both ingots (table 3) was very close to the nominal composition. A typical microstructure (fig. 3) shows a primarily austenitic structure with some areas with slight transformation to martensite. Bands containing partially transformed martensite also were found in the 10Cr alloy. Microprobe scans across these bands indicated that the partial martensite transformation resulted from a 2-pct reduction of Ni content in these areas.

Room-Temperature Tensile Evaluation

The room-temperature tensile tests for the alloys are summarized in table 4. The yield strengths for the annealed 10Cr and 8Cr alloys (37,600 psi and 33,600 psi, respectively) approximated the yield strength of annealed type 304. The specimens not heat-treated had increased yield strength, probably as a result of residual cold work in the materials. Tensile strengths of the annealed specimens and those not heat-treated ranged from 101,400 to 179,800 psi, which is significantly higher than the 85,000 psi found for annealed type 304 stainless steel. Magnetic measurements and the microstructures of the failed specimens showed that the



FIGURE 3. - Microstructure of 10Cr alloy (X 200). Structure is austenitic with slight transformation to martensite.

increased tensile strengths are caused by the formation of deformation-induced martensite. Such deformation-induced martensite can be formed in some stainless steels (i.e., type 301) by plastic deformation. In such alloys, martensite formed during the tensile test can cause high tensile strengths similar to those determined in this investigation. The ductilities of both alloys with and without annealing ranged from 16- to 47-pct elongation, which is a reduction from the 55-pct elongation of type 304 stainless steel. The 1,000 h aging at 700° C

TABLE 3. - Analysis of alloys

Determination	10Cr alloy ¹	8Cr alloy ²
Composition, pct:		
Cr.....	10.2	8.4
Ni.....	10.9	13.0
Si.....	4.8	5.4
Mn.....	0.46	0.68
C.....	0.076	0.075
Composition, ppm:		
O.....	23	32
N.....	21	28
Ferrite No. ³vol pct..	1	1-10

¹Nominal Composition Fe-10Cr-11Ni-5Si-1Mn-0.05C.

²Nominal Composition Fe-8Cr-13Ni-5Si-1Mn-0.05C.

³Approximates the volume percent ferrite or martensite.

TABLE 4. - Tensile properties of substitute alloys at room and high temperature

Alloy and test temperature	Heat treatment	Strength, psi		Ductility, pct	
		Yield, 0.2 pct offset	Tensile	Elongation, 1 in	RA ¹
10Cr alloy: ²					
Room temp.....	None.....	47,300	179,800	43	68
Do.....	Annealed 1 h at 1,100° C	37,600	101,400	16	19
Do.....	Aged 1,000 h 700° C.....	53,300	169,100	20	18
600° C.....	None.....	28,800	65,700	52	71
700° C.....	...do.....	29,700	47,000	33	49
800° C.....	...do.....	21,100	23,600	47	93
8Cr alloy: ²					
Room temp.....	None.....	45,500	160,500	47	78
Do.....	Annealed 1 h at 1,100° C	33,600	151,600	35	37
Do.....	Aged 1,000 h 700° C.....	33,200	156,500	36	41
600° C.....	None.....	29,600	62,800	41	65
700° C.....	...do.....	25,600	40,500	31	48
800° C.....	...do.....	14,100	18,200	60	99
Type 304 stainless steel (12):					
Room temp.....	Annealed.....	35,000	85,000	55	65
600° C.....	...do.....	20,000	50,000	36	NA
700° C.....	...do.....	17,000	36,000	33	NA
800° C.....	...do.....	14,000	22,000	30	NA
Type 410 stainless steel (12):					
Room temp.....	...do.....	40,000	75,000	NA	NA
600° C.....	...do.....	25,000	50,000	25	85

NA Not available. ¹Reduction of area. ²Average of duplicate specimens.

of the 10Cr alloy increased the yield and tensile strengths. The 8Cr alloy changed insignificantly during the aging treatment.

Hot Tensile Evaluation

The hot tensile properties of both alloys also are summarized in table 4. The alloy properties are compared to those for type 304 stainless steel at all three temperatures and to the properties of type 410 stainless steel at 600° C, its useful high-temperature limit. The yield and tensile strengths of both alloys exceeded those of the reference materials at both 600° and 700° C. At 800° C, the yield and tensile strengths of the 10Cr alloy exceeded those for type 304 stainless steel. At 800° C, the 8Cr alloy had equivalent yield strength but a slightly lower tensile strength as compared to the

properties of type 304 stainless steel. Therefore, these substitutes have good hot tensile properties compared to those of type 304 stainless steel.

The hot tensile tests were conducted above the M_d temperature, the highest temperature at which martensite can be formed by deformation. Therefore, during the hot tensile testing, the substitute alloys did not become magnetic by forming deformation-induced martensite, as they had during room-temperature tensile testing.

Stress Rupture Evaluation

The results of the stress rupture evaluation at 600°, 700°, and 800° C are summarized and compared to those for two commercial stainless steels in figures 4 to 6. Both substitute alloys had rupture

strength values between those of type 410 and 304 stainless steels, alloys used for their heat-resisting properties. Although lower than that of type 304 stainless steel, the rupture strengths of the substitutes were significantly higher than that of type 410 stainless steel, a 12-pct-Cr stainless steel used for heat-resisting applications. At all temperatures, the 10Cr substitute possessed higher rupture strength than the 8Cr alloy.

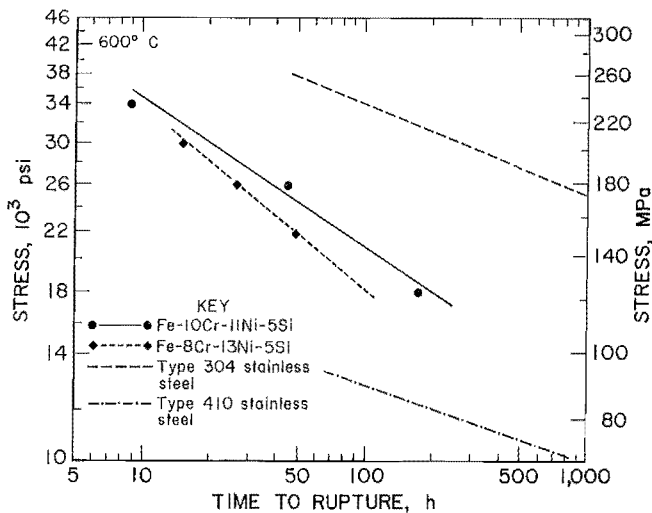


FIGURE 4. - Stress rupture resistance at 600° C. Substitute alloys compared to types 410 and 304 stainless steels (13).

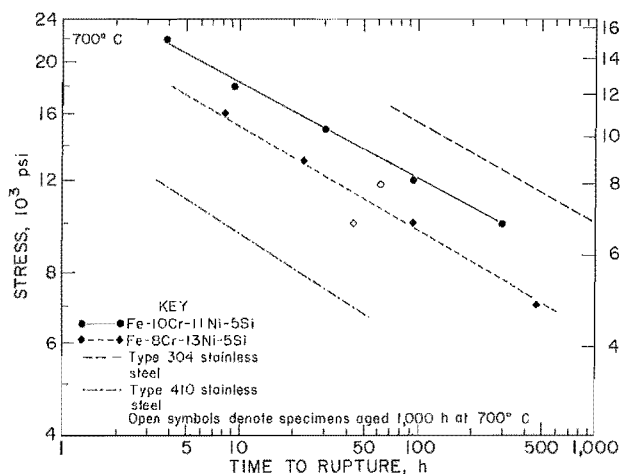


FIGURE 5. - Stress rupture resistance at 700° C. Substitute alloys compared to types 410 and 304 stainless steels (13).

To determine the effects of extended aging, a specimen of each alloy was aged for 1,000 h at 700° C prior to stress rupture testing. As shown by the open symbols in figure 5, both alloys had reduced rupture strengths after aging.

Oxidation Evaluation

The oxidation resistance of the alloys was evaluated and compared with those of two commercial stainless steels using weight gain measurements (fig. 7). The data show that both alloys had lower oxidation rates than did type 410 and 304 stainless steels at 700° and 800° C. The oxidation rates were so low that it was not possible to accurately predict a rate equation for the oxidation of these alloys. The data show that both alloys have sufficient oxidation resistance to substitute for stainless steel.

The effects of aging of these alloys were studied by examining the 700° and 800° C oxidation specimens after 1,000-h exposure. The alloy structure was examined by metallographic techniques and by using data derived from the Magne-Gage. The evaluation showed that the structure of the 10Cr alloy was still partially martensitic after aging. The 8Cr alloy experienced a slight change to

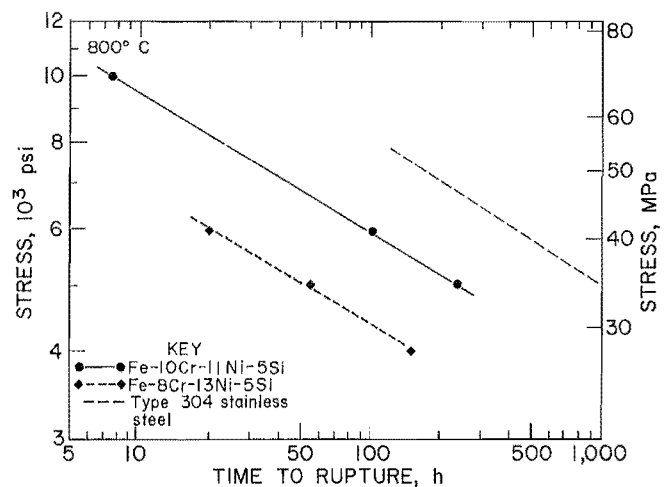


FIGURE 6. - Stress rupture resistance at 800° C. Substitute alloys compared to type 304 stainless steel (13).

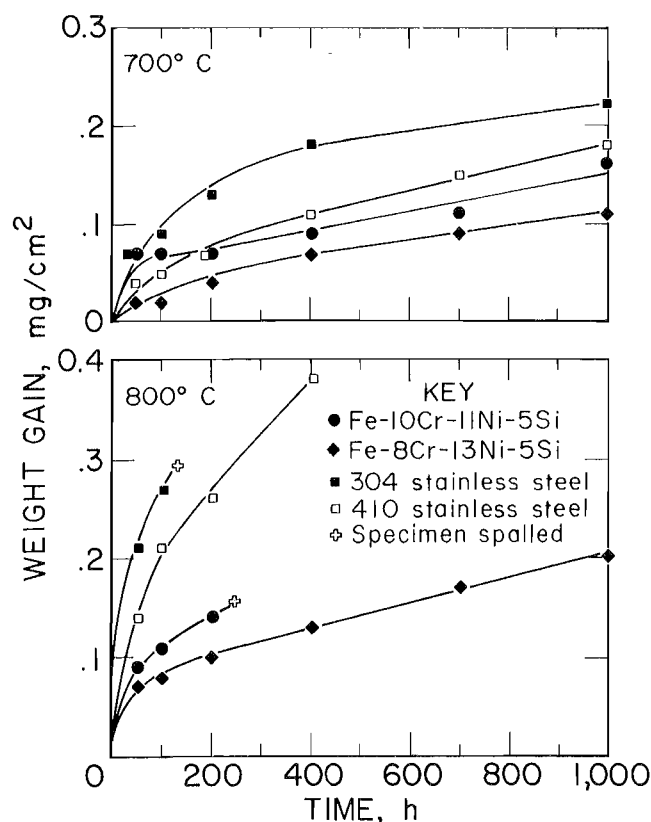


FIGURE 7. - Oxidation rates as measured by weight gain.

martensite after aging. Metallographic and SEM evaluation of the aged alloys showed the formation of intermetallic precipitates that were high in Cr, Ni, and Si in both alloys. Thus, a fully austenitic structure did not appear to be stable for these two alloy compositions because of the appearance of intermetallic precipitates and martensite after a long-term exposure at 700° and 800° C.

Weldability Evaluation

The results of the Varestraint evaluation of alloy susceptibility to weld hot cracking are shown in table 5. To provide a basis for comparison, several specimens of type 304 stainless steel also were evaluated. The 304 specimens withstood 2-pct strain but cracked at 4-pct strain. This 2- to 4-pct cracking threshold is within the normal range for this stainless steel, but it is slightly lower than desired, probably a result of

the lower ferrite content of 3 vol pct instead of the desired 4 vol pct or greater (11). Both alloy substitutes also had weld-hot-cracking thresholds of 2- to 4-pct strain.

The severity of hot cracking also was evaluated through the determination of the maximum crack length (MCL) or total crack length (TCL) at a given strain. In this evaluation at 6-pct strain, the 10Cr alloy had an MCL of 0.6 mm and a TCL of

TABLE 5. - Summary of Varestraint weld-hot-cracking¹ evaluation of substitute alloys²

Strain, pct	Number of cracks	Total crack length, mm	Max crack length, mm
10Cr ALLOY (Fe-10Cr-11Ni-5Si)			
6.....	4	1.3	0.6
4.....	8	2.2	.6
4.....	6	1.1	.3
4.....	4	.6	.4
2.....	0	0	0
2.....	0	0	0
2.....	0	0	0
1.....	0	0	0
8Cr ALLOY (Fe-8Cr-13Ni-5Si)			
6.....	11	6.3	1.0
4.....	3	3.1	.9
4.....	4	1.4	.7
2.....	0	0	0
1.....	0	0	0
1.....	0	0	0
TYPE 304 STAINLESS STEEL (FOR REFERENCE)			
6.....	6	1.8	0.7
4.....	4	.4	.3
4.....	3	.9	.5
4.....	2	.7	.4
2.....	0	0	0
2.....	0	0	0
2.....	0	0	0
1.....	0	0	0

¹Welding conditions:

Current: 95 A for type 304, 75 A for substitute alloys.

Arc voltage: 12 V dc.

Travel speed: 8 in/min.

Electrode: 3/32-in diam; W-2 pct Th.

Shield gas: Ar, 40 ft³/h.

²Results courtesy of Dr. Carl Lundin, University of Tennessee.

1.3 mm, compared to 0.7 mm and 1.8 mm for type 304 stainless steel. The 8Cr alloy had the significantly higher values of 1.0 mm for the MCL and 6.3 mm for the TCL. The results show that, for the onset of hot cracking, both alloys are

equivalent to the reference type 304 stainless steel. However, after crack initiation, the hot cracks propagate more severely in the 8Cr alloy than they do in the 10Cr alloy or in type 304 stainless steel.

CONCLUSIONS

In this study, a series of Fe-(8-10)Cr-(10-14)Ni-(0-8.5)Si-(0-4)Al alloys was evaluated to determine their potential as austenitic substitutes for the stainless steels used for heat-resisting applications. The results of this evaluation of structure, hot-working properties, and oxidation resistance follow:

1. Fe-10Cr-Ni alloys with Si additions were austenitic at Ni levels as low as 10 pct (when the Si was between 4 and 6 pct). Alloys containing Al instead of Si or in combination with Si required 12 to 14 pct Ni to provide the austenitic structure.

2. Many of the alloys hot-worked without cracking. In general, the alloys that contained 2.5 to 8.5 pct Si experienced the least cracking during hot working, and the alloys that contained Al experienced the most cracking during hot working.

3. Additions of 4 pct Al or greater were required in the alloys without Si to provide oxidation resistance at 750° C. The alloys that contained Si as low as 2.5 pct were oxidation resistant at 750° C.

4. For an 8-pct-Cr alloy with 5 pct Si, additions of 12 pct Ni were required for an austenitic structure.

Based on the results of this evaluation, an Fe-10Cr-11Ni-5Si alloy and an Fe-8Cr-13Ni-5Si alloy were selected for more complete evaluation. The following are the conclusions of the evaluation and the alloy comparison to the common types 410 and 304 stainless steels:

1. At room temperature, both alloys have yield strengths equivalent to that of type 304 stainless steel. Room-temperature tensile strengths for both alloys (as high as 179,800 psi for the 10Cr alloy) greatly exceed that of type 410 and 304 stainless steels. The high strengths are the result of deformation-induced transformation of the austenite to martensite.

2. Tensile strengths at 600° and 700° C for both alloys exceed that of type 410 and 304 stainless steel. At 800° C, the yield and tensile strength of the 10Cr alloy exceed that of type 304 stainless steel, but the 8Cr alloy has slightly reduced tensile strength and equivalent yield strength as compared to type 304 stainless steel.

3. Both substitute alloys have stress rupture strengths at 600°, 700°, and 800° C that are between those of types 410 and 304 stainless steel.

4. The oxidation rates at 700° and 800° C for the substitute alloys are less than that for types 410 and 304 stainless steel. Examinations of the alloy microstructures after 1,000-h oxidation exposures show slight instability of both alloys through the formation of intermetallic phases and resulting in partial transformation to martensite in the 10Cr alloy.

5. Both alloys have Vareststraint hot-cracking thresholds of 2 to 4 pct strain, which are equivalent to that of type 304 stainless steel. After crack initiation, the 8Cr alloy propagates the cracks more severely than either the 10Cr alloy or type 304 stainless steel.

This investigation shows that 8Cr and 10Cr austenitic alloys with Si additions have potential for heat-resisting applications. The mechanical properties, oxidation rates, and weld-hot-cracking resistance of these alloys are sufficient for substitutes for stainless steels. However, the results indicate that these alloys are not stable because of the formation of deformation-induced martensite

at room temperature or the formation of intermetallic precipitates and martensite after aging at high temperatures. Research is being continued to further evaluate Al additions and to adjust compositions to minimize instability and still maintain or improve the mechanical properties, oxidation resistance, and weldability of these potential substitute materials.

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APPENDIX.--DATA FROM ALLOY SELECTION EVALUATION

Alloy	Nominal composition, pct ¹				Structure ²	Workability ³	Alloy	Nominal composition, pct ¹				Structure ²	Workability ³
	Cr	Ni	Si	Al				Cr	Ni	Si	Al		
1...	10	10	2.5	0	M	+	22...	10	12	2	0.5	N	-
2...	10	10	3.5	0	M	+	23...	10	12	2	1	N	-
3...	10	10	4	0	P	+	24...	10	12	2	2	N	-
4...	10	10	4.5	0	N	+	25...	10	12	1.5	1.5	N	-
5...	10	10	5.5	0	N	+	26...	10	12	0	1	M	-
6...	10	10	6.5	0	M	+	27...	10	12	0	1.5	M	0
7...	10	10	7.5	0	M	+	28...	10	12	0	2	M	-
8...	10	10	8.5	0	M	+	29...	10	12	0	3	M	+
9...	10	10	2	.5	M	0	30...	10	12	0	4	M	+
10...	10	10	2	1	M	+	31...	10	14	2	.5	N	-
11...	10	10	2	1.5	M	+	32...	10	14	2	1	N	-
12...	10	10	2	2	M	+	33...	10	14	0	1	N	-
13...	10	10	0	.5	M	+	34...	10	14	0	1.5	N	-
14...	10	10	0	1	M	-	35...	10	14	0	2	N	0
15...	10	10	0	1.5	M	+	36...	10	14	0	3	N	-
16...	10	10	0	2	M	+	37...	10	14	0	4	N	0
17...	10	10	0	2.5	M	0	38...	8	10	4	0	M	+
18...	10	10	0	3	M	-	39...	8	10	5	0	M	+
19...	10	10	0	3.5	M	+	40...	8	10	6	0	N	+
20...	10	10	0	4	M	+	41...	8	12	5	0	N	0
21...	10	12	2.5	2.5	N	0							

¹All alloys contain additions of 0.05 pct C and 1.0 pct Mn, balance Fe.

²N (nonmagnetic), ferrite number of ≤ 10 ; P (partially magnetic), ferrite number of 10-20; M (magnetic), ferrite number of ≥ 20 .

³+ (good workability), no cracks; 0 (fair workability), few cracks; - (poor workability), many cracks.